

COST ANALYSIS OF ATMOSPHERE MONITORING SYSTEMS

JUNE 1973



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Prepared under Contract No. NAS 8-28377
by Biotechnology and Power Department
McDonnell Douglas Astronautics Company
Huntington Beach, California

for

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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By
M. M. YAKUT
Biotechnology and Power Department

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FOREWORD

A Cost Analysis of Life Support Systems Study has been conducted by the Biotechnology and Power Department of the McDonnell Douglas Astronautics Company (MDAC), Huntington Beach, California, under Contract NAS8-28377. This project was performed for the NASA-Marshall Space Flight Center under the direction of Mr. James Moses, Deputy Chief, Life Support and Environmental Branch (S&E-ASTN-P).

The final report consists of a summary and four volumes each dealing with a specific life support system area as follows:

| <u>Title</u> | <u>Report Number</u> |
|--|----------------------|
| SUMMARY REPORT | MDC G4630 |
| COST ANALYSIS OF CARBON DIOXIDE CONCENTRATORS | MDC G4631 |
| COST ANALYSIS OF WATER RECOVERY SYSTEMS | MDC G4632 |
| COST ANALYSIS OF OXYGEN RECOVERY SYSTEMS | MDC G4633 |
| COST ANALYSIS OF ATMOSPHERE MONITORING SYSTEMS | MDC G4634 |

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Section 1

INTRODUCTION AND SUMMARY

A methodology was developed to predict realistic relative cost of Life Support Systems (LSS) and to define areas of major cost impacts in the development cycle. Emphasis was given to tailoring the cost data for usage by program planners and designers. Cost estimates can be completed using the developed equations for varying degrees of equipment refinement, as well as comparative costs between different functional methods. This report deals with the cost analysis of two leading atmosphere monitoring systems, namely the Mass Spectrometer and the Gas Chromatograph. A summary of the approach used in developing the cost estimating techniques is presented in the following paragraphs. Included are the cost estimating techniques, the development of cost estimating relationships and the atmosphere monitoring system cost estimates.

The two atmosphere monitoring systems have been quantitatively evaluated. System characteristics, including mass flows through the instruments and performance and physical criteria were also analyzed. Additionally, the status of development of each of the two systems considered and the required advance technology efforts required to bring pre-prototype hardware to an operational status were defined. The equipment classifications used based on the degree of refinement were as follows: 1) working model, 2) low-fidelity prototype, 3) high-fidelity prototype, and 4) flight-qualified system.

The most cost effective development approach was discovered to be with the programs that initially used working models and subsequently low-fidelity prototypes to verify concept workability. The further continuation of the development of the best approaches in the advanced research and technology phase from the low-fidelity to high-fidelity level had the potential of further reducing costs prior to committing funds to produce flight-qualified hardware. It was apparent that the high-fidelity hardware should be included

in the advanced research and technology phase to provide the data required to minimize design changes in the flight production and qualification program. Design changes that occur too late in the development cycle will significantly escalate costs. The advanced research and technology phase, when effectively used, as previously discussed, has the overall effect of improving the production hardware development schedule and reducing the total program cost, including the expense of hardware, system certification, and testing.

The system costs were determined based on the summation of the average derived cost of each individual component for a given subsystem configuration. The system program costs were proportioned based on past recorded Gemini program experience. Cost of low- and high-fidelity LSS prototypes were found to average approximately 5% and 10%, respectively, of the cost of flight-qualified units. However, the advanced state of development of atmosphere monitoring system prototypes and the fact that they generally include miniaturized flight-type electronics, indicates that the cost of currently developed atmosphere monitoring prototypes is approximately 20 to 30% of the cost of flight-qualified systems. Resulting cost data agreed favorably with past equipment costs for other prototype hardware developed in advanced research and technology programs. The cost analysis of atmosphere monitoring systems is presented in the following Sections:

Cost Estimating Techniques

Cost Estimates of Atmosphere Monitoring Systems

Conclusions

Section 2

COST ESTIMATING TECHNIQUES

Cost estimatings were established for both low- and high-fidelity prototypes and flight-qualified-type atmosphere monitoring equipment utilizing the methodology discussed below.

2.1 COST ESTIMATES OF ATMOSPHERE MONITORING SYSTEM PROTOTYPES

The cost of low-fidelity atmosphere monitoring system prototypes was found to depend on its degree of sophistication and utilization of available space hardware and/or commercial components. A cost estimate approximately equal to half that of a corresponding high-fidelity prototype was allocated to low-fidelity prototypes. High-fidelity prototypes were assumed to be similar in construction to the first test system produced in a flight program which has not undergone any qualification or reliability testing. The cost of the high-fidelity prototype was obtained by excluding those cost items which are pertinent solely to flight articles. Generally, cost of low- and high-fidelity life support system prototypes constituted 5% and 10%, respectively, of the cost of a corresponding flight-type system. However, the state of development of the types of Gas Chromatograph and Mass Spectrometers considered in this study is already more advanced than that of low- and high-fidelity prototypes of other life support systems. Consequently, low-fidelity prototypes, which have been considered for other life support systems, are not presented in this report. The cost of a high-fidelity prototype is estimated to be approximately 20 to 30% of the cost of flight-type systems. A more detailed discussion of prototype cost estimating is presented in Report No. MDC G4630, "Cost Analysis of Life Support Systems - Summary Report".

2.2 COST ESTIMATES OF FLIGHT-QUALIFIED ATMOSPHERE MONITORING SYSTEMS

The atmosphere monitoring systems cost estimating techniques were developed by 1) identifying the physical and performance characteristics of each of the system components, 2) establishing or utilizing existing cost estimating relationships (CER's) for each of the components considered, and 3) the summation of equations for respective system components to establish the total system cost estimation. The U. S. Bureau of Standards Consumer Price Index was used to account for inflation and economic escalation.

The methodology used in the development of CER's is as follows:

1. The components were analyzed to determine which physical or performance characteristics might prove useful as predictive variables.
2. Costs were arrayed graphically against the candidate variables either singly or grouped. The most promising of these arrays were selected on the basis of a subjective analysis which considers the appropriateness of the variables, the form and slope of the curves, and the relative aspects of the component costs.

The derivation of a typical life support component CER is presented in detail in Report No. MDC G4630. Individual CER's for respective system components were summed up to establish the total system cost estimating. The validity of derived CER's was verified when they were applied to a number of Skylab components and were found to agree favorably with actual cost data.

A system schematic and a component identification list were prepared for each of the two atmosphere monitoring systems. System and process descriptions, including system performance and characteristics, were also given. The physical and performance parameters were identified for use in formulating the cost estimating relationships. Recurring CER's were then developed and computed for each of the system subassemblies and summed up to obtain the integrated system recurring cost estimates. The system's non-recurring

CER's were computed on an integrated system basis. The major influencing parameter for the non-recurring CER's was found to be the number of component types in the system.

2.3 COST ELEMENT STRUCTURE

The cost element structure, comprising the detailed recurring and non-recurring cost functions, provides visibility of the total project expenditures and permits identification of the significant project costs. The definition of cost-related terms used in this report is given in Section 2.5.

Table I presents a breakdown of typical life support system expenditures, as encountered in the Gemini Program, divided in the respective recurring and non-recurring items. The major recurring cost item is that of flight hardware production. The major non-recurring costs are those related to Design, AGE, and Prime Contractor's specification and procurement efforts.

2.4 EFFECT OF INFLATION ON COST ESTIMATES

A major inherent feature of the methodology which is highly critical to the accuracy of the results obtained pertains to inflation and economic escalation. Since computed CER's are based on specific year dollars, they must be inflated to the proper year in order to obtain realistic future program values. Due to the lack of a specific aerospace price index, the yearly dollar value adopted in this report was considered to correspond to the Consumer Price Index shown in Figure 1, based on data published by the U. S. Bureau of Statistics.

2.5 COST-RELATED DEFINITIONS

The terminology used in this study is that practiced by the McDonnell Douglas Corporation. In order to assist users of the report who are familiar with different terms or groupings of cost-related activities, the following definitions are presented:

TABLE I - REPRESENTATIVE LIFE SUPPORT SYSTEM EXPENDITURE BREAKDOWN

| NON-RECURRING | % | RECURRING | % |
|--|-------|--|-------|
| Design | 16.68 | Flight Hardware Production | 54.56 |
| Subcontractor General & Administrative | 8.62 | Subcontractor G&A | 9.22 |
| Subcontractor Fee | 3.62 | Subcontractor Fee | 3.88 |
| Program Management | 1.24 | Program Management | 1.36 |
| System Engineering | 5.25 | Sustaining Engineering | 1.96 |
| Development Test | 3.44 | | |
| Qualification Test | 2.54 | | |
| Reliability Test | 4.09 | | |
| AGE | 18.45 | | |
| Tooling | 3.87 | Sustaining Tooling | 1.69 |
| Non-accountable Test Hardware | 1.67 | | |
| Specifications, Vendor Coordination and Procurement Expenses | 13.62 | Specifications, Vendor Coordination and Procurement Expenses | 15.49 |
| System Integration | 8.36 | System Integration | 7.15 |
| Prime's Testing | 8.17 | Minor Subcontracts | 4.69 |
| Minor Subcontracts | 0.38 | | |
| | <hr/> | | <hr/> |
| TOTAL | 100 % | | 100 % |

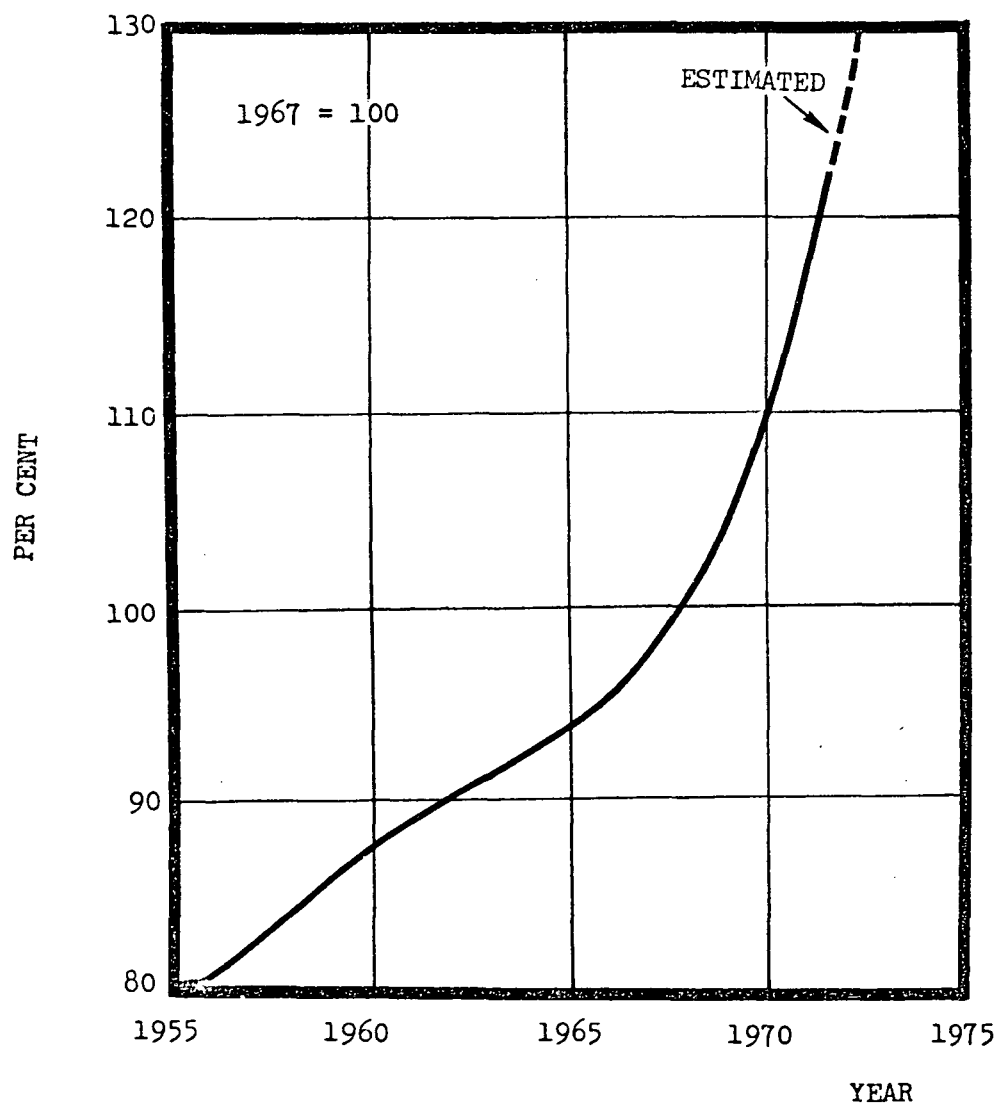


FIGURE 1- Consumer Price Index
(Source: U. S. Bureau of Labor Statistics)

1. Engineering Design - involves the design and analysis of individual components and assemblies in the life support system.
2. Program Management - relates to planning, organizing, directing and controlling the project. Includes scheduling deliveries, coordinating changes and monitoring problem areas.
3. System Engineering - involves system design as opposed to component or assembly design. Includes design, analysis design support, and total system non-separable hardware design and integration effort.
4. Development Testing - involves testing with breadboard and prototype hardware that is required to evaluate component and assembly design concepts and performance.
5. Qualification Testing - deals with formal qualification testing to ensure that components and assemblies provided meet mission performance and design requirements.
6. Reliability Testing - includes component and assembly life cycle and failure analysis testing to ensure operation of the system for the required mission duration.
7. Tooling - involves the design, fabrication and maintenance of component and assembly tools.
8. Non-Accountable Test Hardware - includes prototype units, breadboards, operational mock-ups and other non-deliverable development hardware items.
9. Aerospace Ground Support - includes design and fabrication of system test and servicing, system handling and checkout and hardware necessary during acceptance testing and launch operations.
10. Sustaining Engineering - includes incorporation of changes, modifications to design and contractor's project engineering design.
11. Subcontractor General and Administrative - includes overhead expenses charged as fixed percentages of all other costs.
12. Subcontractor Fee - involves the fee charged by the subcontractor as negotiated at beginning of the contract.
13. Minor Subcontractor - includes procurement costs for minor valves, lines and other required miscellaneous parts.
14. Prime Contractor Costs - include specifications, vendor coordination, procurement and documentation expenses.

15. Recurring Costs - recurring expenditures are divided into the Prime Contractor and Major Subcontractor costs. The Prime Contractor efforts involve primarily the incorporation of the life support systems into the spacecraft. The Major Subcontractor costs are broken into Sustaining Engineering, Tooling and System Production. The System Production expenditures are segregated into subsystems and these are in turn segregated into components.
16. Non-recurring - non-recurring expenditures for each life support subsystem are segregated into Prime Contractor and Major Subcontractor efforts. The Prime Contractor effort involves specification, coordination and integration of the system into the spacecraft. The Major Subcontractor effort is divided into Design and Development, AGE, Program Management and System Engineering, Test Operations and Hardware. The Design and Development costs are segregated into major subsystems.

Section 3

ATMOSPHERE MONITORING SYSTEMS

The design of manned spacecraft life support systems for extended duration requires the monitoring and removal of atmospheric contaminants to insure a purified, breathable atmosphere. The system must cope with a wide variety of compounds produced both metabolically and from the vehicle systems. The presence of certain trace contaminants in closed space cabin atmospheres can have very serious consequences, leading to loss of crew efficiency, incapacitation; and even mission abort. Consideration of these possibilities has lead to the definition of lists of critical contaminants, development of monitoring procedures, and control of allowable materials to prevent excessive off-gassing. Lists of contaminants which have been found in closed manned chamber tests and manned space missions have been developed. On extended missions, regenerable adsorption beds and catalytic oxidizers have been proposed. The criteria developed and results of contaminant measurements in closed-chamber tests of manned systems are applicable to future manned space missions. Particularly, the Space Shuttle and associated spacecraft must meet requirements for acceptable atmospheric contaminants with cost-effective definitions of material limitations, to allow a variety of payloads; of preflight checkout procedures to allow efficient turn-around between missions; and of in-flight monitoring instrumentation. Table II lists and summarizes the trace contaminants found in the NASA/MDAC 90-day test. This table lists the major compounds which were tested for, the concentration limits established by the NAS/NRC ad hoc committee, and the test findings. Compounds, together with common alternate names, are listed by molecular weight. With the exception of complex organic compounds, chemical formulas are given. The lower contingency level values established by the ad hoc committee are given, where applicable, in millimoles per 25 m³, which is essentially equivalent to ppm at sea level.

In selecting an instrument for gas analysis two major requirements must be considered. The first is the capability to sense a large number of gases which

TABLE II
SPACE CABIN ATMOSPHERIC CONTAMINANTS

| Mol. Wt. | Name | Alternate | Formula | MRC/HAS 90-day Level ppm (1) At Sea Level | Found in 90-day Test ppm (1) at Sea Level or P/NP | | | Possible Source |
|----------|---------------------|---------------------|--|--|--|---------|-----------|--|
| | | | | | Cabin | Sil Gel | Mol Sieve | |
| 16 | Methane | | CH ₄ | - | 198 | - | - | Metabolic Product |
| 17 | Ammonia | | NH ₃ | 75 | 2 | - | - | Decomposition of urea |
| 28 | Carbon monoxide | | CO | 60(5) | 18 | - | - | Metabolic product |
| 30 | Formaldehyde | | HCHO | 0.1 | NP(2) | - | - | Metabolic product |
| 30 | Nitric Oxide | | NO | - | (3) | - | - | Decomposition of NH ₃ in catalytic oxidizer |
| 32 | Methanol | Methyl alcohol | CH ₃ OH | - | F | - | - | Metabolic product |
| 34 | Hydrogen Sulfide | | H ₂ S | - | NP | - | - | - |
| 46 | Nitrogen Dioxide | | NO ₂ | - | 0.07(3) | - | - | Decomposition of NH ₃ in catalytic oxidizer |
| 46 | Ethyl Alcohol | Ethanol | C ₂ H ₅ OH | - | 1.0 | - | - | Metabolic product |
| 48 | Ozone | | O ₃ | - | NP | - | - | - |
| 58 | 2-Methyl Propane | Isobutane | (CH ₃) ₃ CH | - | - | - | - | Metabolic product; solvent |
| 58 | 2-Propanone | Acetone | CH ₃ CO ₂ H | 10 | 1.6 | P | P | - |
| 60 | Ethyl Acetate | Acetic acid | CH ₃ CO ₂ H | - | NP | - | - | Pretest cleaning or solvents |
| 60 | 2-Propanol | Isopropyl alcohol | CH ₃ CO ₂ H | - | F | - | - | - |
| 64 | Sulfur dioxide | | SO ₂ | - | NP | - | - | - |
| 71 | Chlorine | | Cl ₂ | - | NP | - | - | - |
| 72 | 2-Butanone | Ethyl methyl ketone | - | 20 | 0.2 | - | - | Pretest Cleaning or solvents |
| 72 | 2-Methyl butane | Isopentane | CH ₃ (CH ₂) ₃ CH ₃ | - | - | - | - | - |
| 72 | Pentane | | CH ₃ (CH ₂) ₃ CH ₃ | - | - | - | - | - |
| 74 | 2-Butanol | Butyl alcohol | CH ₃ (CH ₂) ₃ CH ₂ OH | 10 | F | F | P | Pretest cleaning or solvents |
| 78 | Benzene | | CH ₂ Cl ₂ | - | - | - | - | - |
| 84 | Cyclohexane | | CH ₃ (CH ₂) ₄ CH ₃ | - | - | - | - | - |
| 85 | Dichloromethane | Methylene chloride | CH ₂ Cl ₂ | 25 | F | P | P | - |
| 86 | 2,2-dimethyl butane | Neo-Hexane | CH ₃ (CH ₂) ₄ CH ₃ | - | F | - | - | - |
| 86 | Hexane | | CH ₃ (CH ₂) ₄ CH ₃ | - | - | - | - | - |
| 86 | 2-Methyl butanone | | CH ₃ (CH ₂) ₄ CH ₃ | 20 | NP | - | - | - |
| 88 | Dioxane | | CH ₂ :CCl ₂ | 10 | NP | - | - | - |
| 92 | Methyl benzene | Toluene | CH ₂ :CCl ₂ | - | 0.10 | P | P | Pretest cleaning or solvents |
| 97 | 1,1-Dichloroethene | Vinylidene chloride | CH ₂ :CCl ₂ | 6(4) | NP | - | - | - |
| 98 | 1-Heptene | | Cl CH ₂ :CH ₂ Cl | - | - | - | - | - |
| 99 | 1,2-dichloroethane | Ethylene chloride | Cl CH ₂ :CH ₂ Cl | - | 0.17 | P | P | Pretest cleaning or solvents |

TABLE II (Continued)

SPACE CALIN ATMOSPHERIC CONTAMINANTS

| Mol. Wt. | Name | Alternate | Formula | NRC/HAS 90-day Level ppm(1) | Found in 90-day Test ppm (1) at Sea Level or F/NF | | | Possible Source |
|----------|---------------------------------------|------------------------|--|-----------------------------------|--|---------|------------|-----------------|
| | | | | | Cabin | Sil Gel | Mol. Sieve | |
| 100 | Heptane | Isobutyl methyl ketone | $\text{CH}_3(\text{CH}_2)_5\text{CH}_3$ | - | F | - | - | - |
| 100 | 4-Methyl-2-Pentanone | | | - | - | P | P | - |
| 102 | 2-Ethyl-1-butanol | O-xylene | C_8H_{10} | - | - | F | P | P |
| 106 | 1,2-Dimethyl benzene | | | - | NF | - | P | - |
| 106 | 1,3-Dimethyl benzene | | | - | F | - | - | - |
| 106 | 1,4-Dimethyl benzene | | | - | P | P | - | - |
| 114 | Octane | Chloroform | $\text{CH}_3(\text{CH}_2)_6\text{CH}_3$ | - | - | P | P | - |
| 119 | Trichloromethane | | | 5 | F | - | - | - |
| 129 | Dichloroacetylene | Trichloroethylene | $\text{Cl}_2\text{CHCO}_2\text{H}$ | tr(4) | NF | - | - | - |
| 131 | Trichloroethene | | | 10 | NF | - | - | - |
| 154 | Tetrachloromethane | Carbon tetrachloride | CCl_4 | - | - | - | P | P |
| 167 | Acetic acid, nitrile | | | - | - | P | - | P |
| 187 | Trichlorotrifluoroethane | Freon 113 | Cl_3CCF_3 $\text{Cl}_2\text{CFC ClF}_2$ | - | 8.0 | F | P | P |
| 187 | 1,1,2-Trichloro-1,2,2-Trifluoroethane | | | 1000 | NF | - | - | - |

NOTES: (1) Units are actually millimoles per 25 cu meters which is equivalent to parts per million at sea level pressure.

(2) Measurement sensitivity may not have been adequate to detect formaldehyde at stated level (0.1 millimoles per 25 m³)(3) Total oxides of nitrogen were read, indicated here under NO₂.

(4) These values established by verbal request of ad hoc committee.

(5) The value for carbon monoxide limit stated in Reference 1 (15 millimoles per 25 m³) was revised per verbal request of the ad hoc committee to 60 millimoles per 25 m³ for the 90-day test.

are most commonly found in the atmosphere, and the second is the growth capability of the instrument to enable detection of additional compounds that may be specified at a later date, as well as to provide information to identify unexpected contaminants. Gas analysis equipment with such capabilities fall in three distinct categories: 1) Absorption Spectroscopy, 2) Mass Spectrometry, and 3) Gas Chromatography. Instruments utilizing absorption spectroscopy are characterized by the use of the selective absorption bands of the various gases. Absorption Spectroscopy Systems include infrared, molecular resonance and microwave spectrometry techniques. Wide use of these systems is being made for the detection of specific components that have distinctive absorption bands. Infrared CO_2 detector which utilizes the absorption of CO_2 at 4.3 microns is an example of this type of units. However, a serious disadvantage of infrared devices is posed by some gases masking the absorption peaks of other gases. For example, CO cannot normally be detected by this technique since it would be masked by the presence of N_2O which displays an absorption band at essentially the same wave length.

The disadvantages cited for absorption spectroscopy are not shared by the other two major analysis methods: Mass Spectrometry and Gas Chromatography. Mass Spectrometers have long been used in the petroleum and chemical industries. Gas Chromatography also has found widespread use in process industries. Both techniques have been regarded as reliable means of analysis. Their use in spacecraft applications, previously in unmanned vehicles and currently as an experiment in the Skylab Program, has been mainly involved with miniaturizing the units to reduce their size and power requirements. Subsequently, the number of contaminants monitored by either a Mass Spectrometer or a Gas Chromatograph has been limited to few essential gases. For example, the Perkin-Elmer Company developed a four-gas Mass Spectrometer, sensing O_2 , N_2 , CO_2 and water vapor. Other units have been since developed with capabilities to sense six or seven gases. A new unit is now under development which is said would be capable of monitoring up to forty trace contaminant gases. The new unit will be a scan type Mass Spectrometer and will not be larger in size than the current

4- to 7-gas Mass Spectrometers. The comparative characteristics of the two systems considered, Mass Spectrometer and Gas Chromatograph, are given in Table III which also presents the physical differences, operational characteristics and status of each system.

TABLE III. - COMPARISON OF ATMOSPHERE MONITORING SYSTEMS

| SYSTEM CHARACTERISTICS | MASS SPECTROMETER | GAS CHROMATOGRAPH |
|---|--|---|
| Number of monitored gases Monitored species, typical | 4, 6 or 7 H ₂ , CO ₂ , N ₂ , H ₂ O, F-11, F-12, F-114, and total contaminants with m/e between 50 and 120 | 23 gases, with two columns. H ₂ , O ₂ , N ₂ , CH ₄ , CO, CO ₂ , H ₂ O and number of trace contaminants. |
| Concentration Range | 0.5 to 50 PPM | 10 PPM to 100% Full Scale |
| Accuracy | 0.5 PPM: + 100% 5 PPM: ± 20% 50 PPM: ± 10% | 3% |
| Warm-up Time | 30 Minutes | 60 Minutes |
| Operating Life | 60 days continuous without filament failure | 180 days |
| Volume | 1000 In ³ | 400 In ³ |
| Weight | 15 Lbs | 10 Lbs |
| Power | 25 Watts | 10 Watts |
| System Operation | 1. Sample ionized into charged particles with varying m/e ratios. 2. Magnet used to separate particles with specific m/3 ratios. | 1. Sample, in a carrier gas, passed through a packed column. 2. Preferential absorption of components of sample causes different rates of elution. 3. Detector-amplifier produces signals proportional to concentration of concentration of components in sample. |
| System Status/Availability | 1. Flight prototypes developed for 4, 6 and seven gases. 2. Six-gas unit to be used in Skylab experiment. | 1. Flight units developed only for unmanned flights such as one for Surveyor to analyze |

TABLE III. - COMPARISON OF ATMOSPHERE MONITORING SYSTEMS (Continued)

| SYSTEM CHARACTERISTICS | MASS SPECTROMETER | GAS CHROMATOGRAPH |
|------------------------|---|--|
| | <p>3. Six-gas Mass Spectrometer successfully tested in NASA/MDAC 90-Day Test. Unit also actuated cabin two-gas controller.</p> <p>4. Forty-gas trace contaminants Mass Spectrometer currently under development. Low-Fidelity prototype expected in one year.</p> <p>None Anticipated</p> | <p>lunar soil.</p> <p>2. A Gas Chromatograph/Mass Spectrometer combination is currently under development for Viking Program.</p> <p>3. A Low-Fidelity prototype to monitor cabin trace contaminants was developed by NASA/MELPAR, but not used. Renewed development of a flight prototype similar to the NASA/MELPAR unit is required</p> |
| Development Problems | | |

COST ESTIMATING OF ATMOSPHERIC MONITORING SYSTEMS

4.1 MASS SPECTROMETER:

Process Description:

The principle of Mass Spectrometry involves the ionization of a sample into charged particles which are separated into their characteristic mass to charge ratios and then detected. Mass Spectrometers currently under development are of the magnetic field type shown in Figure 2, in which the particles are accelerated by an electric field. Each mass to charge ratio is accelerated to a characteristic velocity dependent upon the accelerating voltage. They then pass through a magnetic field where the degree of deflection is a function of the mass to charge ratio of the particles. The field separates the ions into beams, each of a different mass to charge ratio. By varying the accelerating voltage the resultant beams are successively directed through a resolving slit and onto a collector. The resultant current is amplified and provides a measure of the number of ions at each mass to charge ratio.

Current Mass Spectrometer Systems include a number of small 90° magnetic sector type units which provide four, six or seven simultaneous and linear type voltages that are proportional to the partial pressures of a corresponding number of gases. Atmospheric gases measured by these Mass Spectrometers include H_2 , CO_2 , O_2 , N_2 , N_2O , F-11, F-12, F-114 and total contaminants. The total contaminants include constituents with mass-to-charge ratios of 50 to 120. For the purpose of this study, a six-charge Mass Spectrometer will be considered. Modifications to existing Mass Spectrometers will then include the collector configuration and expected repackaging for the required application.

A basic schematic block diagram of the system is shown in Figure 3 which may be conveniently divided into two subsystems; the analyzer subsystem and the electronics subsystem. The analyzer subsystem consists of that part of the device which admits the gas to be sampled to the system, ionizes the sample to form the charged particles which are then resolved in the magnetic sector, and maintains the internal vacuum necessary for operation of the instrument. The electronics subsystem consists of the various circuits required to supply voltages and currents for the operation of the analyzer as well as

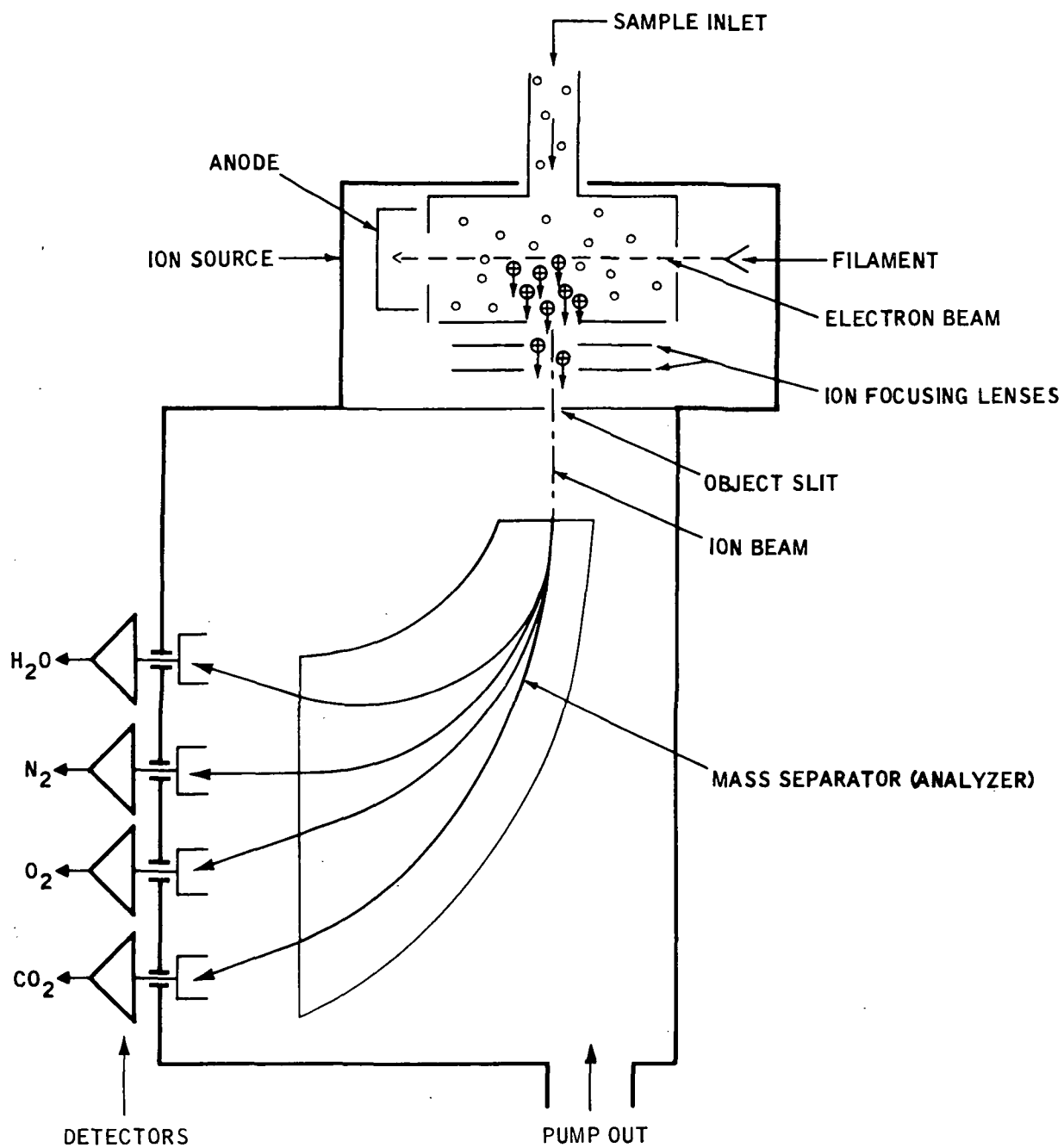


FIGURE 2. MAGNETIC FIELD TYPE MASS SPECTROMETER

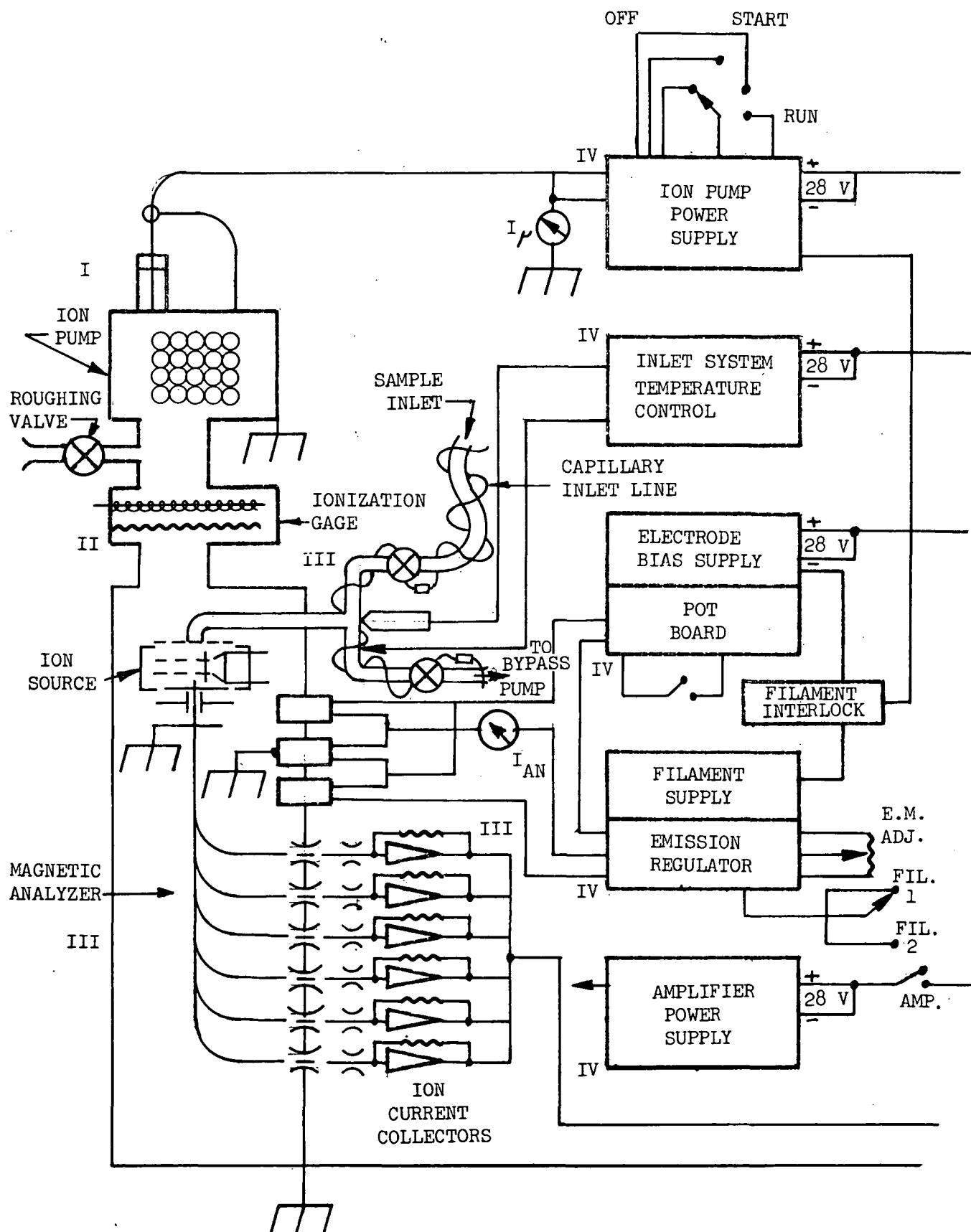


FIGURE 3. MASS SPECTROMETER SYSTEM SCHEMATIC

for the amplification of the ion current outputs. The two subsystems are housed in a system enclosure with the necessary inputs and outputs. A more detailed description of the system is given in the following paragraphs.

The inlet system consists of a viscous-flow capillary line that samples the atmosphere at one standard atmosphere and reduces the pressure to seven torr by means of the pressure drop in the flow channel. At the point where the nominal pressure is seven torr, the flow is sampled by an orifice that provides a molecular flow into the ion source. The capillary line is approximately six feet in length, which allows some flexibility in the location of the sampling point relative to the mass spectrometer. The ion source, which is contained in the analyzer housing is a dual filament, nonmagnetic type that employs two electron guns that are mounted in an orthogonal configuration. The filaments are 0.003 inch diameter tungsten-rhenium wires. The ion source has a limited gas conductance to isolate the ionizing region from undesirable variations in the filament and ion pump regions which can cause variations in the sensitivity. The ions exit from the ion source at the exit slit and are injected into the magnetic sector region of the analyzer. This is a 90-degree magnetic sector which disperses the ion beam according to the mass-to-charge ratios of the ions while correcting to first order for the angular spread of the ion beam. Six ion current collectors are located on the focal plane of the analyzer and receive the ions from six atmospheric constituents. The positions of the collectors are adjustable to facilitate the simultaneous collection of the six species. The magnetic field of 4000 gauss is supplied by a permanent magnet.

A vacuum envelop houses the ion source and the magnetic sector. It is typically a thin walled stainless steel housing which is electrically accessible through feedthroughs. The electronics circuits necessary for the operation of the analyzer include the following:

- a. An electrode bias supply which provides voltages for the ion source focusing electrodes.

- b. A filament supply and emission regulator for the control of the ionizing electron beam.
- c. The six electrometer amplifiers for amplification of the ion current signals.
- d. A ± 10 volt power supply for the B+ and B- voltages that operate the electrometers.

Multiple pin headers introduce voltages from the ion source electronics and feed them to the filaments and to the various focusing electrodes, while single pin feedthroughs transmit the ion currents from the ion current collectors to electrometer amplifiers which amplify the small ion currents to the levels required for output.

Each of the collected ion currents is amplified to the required output level by an all solid-state electrometer amplifier. Each amplifier is set for the sensitivity commensurate with the expected sample range of that atmospheric component. These amplifiers have a high input impedance and utilize 100% current feedback to obtain an output which is essentially independent of any active devices. The output voltage is equal to the input current multiplied by the feedback resistance.

In addition to the ion current amplifiers the sensor system support electronics subsystem consists of three modules which provide the electronic functions necessary for the operation of the analyzer. First, there is a filament supply and emission regulator which supplies an AC voltage to the filament. This is a closed loop control system which senses the ionizing current that is collected at the anode of the ion source and uses this as feedback current to control the filament power so that the ionizing current remains constant. System considerations also require that this module be floated above ground at the anode potential. An inverter is used for this and its pulse width modulated output drives the filament.

The electrode bias supply provides the voltages to the various focusing electrodes in the ion source. It consists of a single inverter with a multiple winding output. Series voltage regulators operate off of two of the rectified outputs and these are used to compensate for variations in two of the other outputs. The result is three stacked high voltage outputs, two that are regulated and one that is unregulated. These outputs are loaded by a resistance voltage divider network with potentiometers which are cabled to the ion source headers.

The detector power supply consists of a single free running inverter which drives regulators that supply +10 and -10 volts to the detectors.

System Performance And Characteristics:

The physical, performance and interface characteristics of the Mass Spectrometer System are as follows:

| | |
|----------------------------|--|
| Monitored Species | Six gases with m/e ratios between 2 and 120. Typical gases are H ₂ , CO ₂ , N ₂ , H ₂ O, F-11, F-12, F-114 and total contaminants with m/e between 50 and 120 |
| Concentrations Range | 0.5 to 50 PPM |
| Accuracy | 0.5 PPM: ±100% 5 PPM: ±20% 50 PPM: ±10% |
| Sample Gas Loss | 250 torr cc/sec at one atmosphere. |
| Maximum Operating Pressure | 800 torr with 1 atmosphere capillary. |
| Ion Source Pressure | The ion source can maintain linear operation up to a pressure of 2×10^{-4} torr. |
| Differential Pressure | 100:1 (ion source pressure to analyzer pressure ratio). |
| Outputs | Six simultaneous, linear 0 to -5 volts. |

| | |
|-----------------------------|---|
| Dynamic Range | 200 torr for O ₂ , 0.1 to 50 torr for H ₂ O, CO ₂ , H ₂ , Freons, THC, or total contaminants. |
| Power | 25 watts |
| Weight | 15 pounds |
| Volume | 0.6 ft. ³ |
| Operating Temperature Range | 40 to 90°F |
| Warm Up | 30 minutes for full temperature stabilization. |
| Expected Operating Life | Sixty days of continuous operation without filament failure. |

Cost Estimating Relationships:

The Mass Spectrometer system components have been grouped in four groups, designated as I through IV, as shown in the system schematic, Figure 3. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior years dollar values.

Recurring CER's:

1. The Ion Pump:

The Ion Pump used with the Mass Spectrometer is a special type unit which was found to be a good compromise between size and pumping power for the application. As the size of the pump is not expected to vary appreciably with spacecraft size, mission duration or the number of species expected to be monitored, the currently used unit will be considered applicable to other size Mass Spectrometers. The said unit is a flight type pump with a capacity of 4 liters/second. The ion pump CER to be represented by the following non-variable relation:

$$\text{Ion pump fabrication cost} = 4000 \quad \text{Dollars}$$

2. Ionization Gage:

The ionization gage, added in the tube that connects the analyzer to the ion pump, is also considered as a special non-variable size item which, similar to the ion pump, has a relatively fixed cost. A tube is welded into the ionization gage chamber for rough pumping the analyzer, with a valve added to the line to close it off after rough pumping. The cost of the ionization gage, including the valve is given as follows:

$$\text{Ionization gage fabrication cost} = 2500 \quad \text{Dollars}$$

3. Analyzer Assembly:

The CER for the analyzer assembly, comprised of the sample inlet system, ion source analyzer magnet and ion collector assembly is given as follows:

$$\begin{aligned} \text{Analyzer assembly fabrication cost } C \\ = 4000 + 500 N_c \quad \text{Dollars} \end{aligned}$$

where N_c = number of ion collector per assembly.

Substituting the value of $N_c = 4$ in the CER yields:

$$C = 400 + 2000 = 6000 \quad \text{Dollars}$$

4. Electronic Equipment:

The CER for the fabrication costs of the electronic equipment, mounted on printed circuit boards and including packaging and panel construction, has been based on current similar electronic hardware manufacturing costs and is given as follows:

$$\text{Electronic equipment fabrication cost} = 150 N_B + 500 \quad \text{Dollars}$$

where, N_B = number of printed circuit boards per assembly. The Mass Spectrometer System was found to require the following printed circuit boards: 1) amplifier power supply, 2) inlet system temperature control 3) filament supply, 4) electrode bias supply, and

5) ion pump power supply. Substituting the value for $N = 5$ in the above CER yields the following:

$$C = 150 \times 5 + 500 = 1250 \quad \text{Dollars}$$

Integrated Mass Spectrometer System's Recurring CER:

The integration costs of components and assemblies into the Mass Spectrometer System are obtained by utilizing the system's recurring CER as defined in previous volumes of this report. Applying the said CER, then

$$\text{First unit cost } C_F = 1.833 \times 1.1 \times (4000 + 2500 + 6000 + 1250)$$

$$C_F = 27,724 \quad \text{Dollars}$$

and assuming the production of two flight-type units, one for flight and one for back-up, then the total hardware cost is given by:

$$C_T = 27,724 \times (2)^{1-0.1047} = 51,428 \quad \text{Dollars}$$

Integrated Mass Spectrometer System's Non-Recurring Cost:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on typical cost breakdown ratios, which are based on actual cost data collected in a space vehicle hardware production program. A system design CER has been developed for the Mass Spectrometer which combines the effects of both mechanical and electronic system designs. The analysis of a number of cost influencing parameters indicated that mechanical engineering design CER is mainly a function of the number of component types (N) in the system. For electronic system design the cost is a function of the number of printed circuit boards involved. The combined design CER is thus given by the following relation:

$$\text{System design cost } C = 34,935 N + 3000N_0 \quad \text{Dollars}$$

where

N = number of component types designed, however since all components have been already designed except for modification of of collector and repackaging, N is considered = 1, and

N_B = number of printed circuit boards = 5. Substituting the values of variables in the CER yields the following:

$$C = 34,935 + 3000 \times 5 = 49,935 \quad \text{Dollars}$$

Values of other non-recurring cost items are listed in Table IV, which also shows the breakdown of recurring cost items based on the production of two flight hardware units. All cost figures are in estimated January 1972 dollars.

4.2 GAS CHROMATOGRAPH

The gas chromatograph consists of basically three elements: a sample device, a chromatograph column assembly which physically separates the sample constituents, and a detector-amplifier which produces an electrical signal whose magnitude is proportional to the concentration of each component in the sample. The chromatograph column normally consists of a length of coiled tubing filled with a solid support medium which preferentially adsorbs the individual components of the sample, causing them to pass through the column at different rates of speed by a continuous flow of carrier gas. Some columns consist of adsorption materials such as Silica Gel, Alumina, or Molecular Sieve and other types of columns consist of a solid support, usually crushed firebrick or Teflon, upon which has been placed a thin layer of a high boiling point liquid. These partition liquid columns provide good separation for organics and hydrocarbons, whereas the adsorption types are normally used for separation of the fixed gases. The separation ability of the column is a function of its length, the operating temperature, the flow rate of the carrier gas and the type of material which it contains. The output signal from the detector is a series of peaks, each peak representing a separate constituent. This signal is normally amplified and displayed on a strip chart recorder, or can be telemetered to Earth. By properly gating the output signal, particular constituents such as oxygen, nitrogen and carbon dioxide can be read out on individual indicators, thereby providing a continuous reading for these key constituents within the capsule. As the individual components

TABLE IV - MASS SPECTROMETER SYSTEM COST BREAKDOWN

| Non-Recurring | | Recurring | |
|---|---------|---|--------|
| System Engineering Design | 49,935 | Flight Hardware Production (2 units) | 28,059 |
| Subcontractor General and Administrative | 25,816 | Subcontractor G&A | 4,742 |
| Subcontractor Fee | 10,836 | Subcontractor Fee | 1,995 |
| Program Management | 3,745 | Program Management | 700 |
| System Engineering Development Test | 15,729 | Sustaining Engineering | 1,008 |
| Qualification Test | 10,281 | | |
| Reliability Test | 7,590 | | |
| AGE | 12,234 | | |
| Tooling | 55,228 | Sustaining Tooling | 8,690 |
| Non-accountable Test Hardware | 11,585 | | |
| Specifications, Vendor Coordination and Procurement Expense | 4,994 | Specifications, Vendor Coordination and Procurement Expense | 7,966 |
| System Integration | 40,797 | System Integration | 3,677 |
| Prime's Testing | 25,017 | | |
| Minor Subcontracts | 24,468 | Minor Subcontracts | 2,412 |
| | 1,149 | | |
| Total | 299,410 | | 51,428 |

Total Mass Spectrometer System Cost = 299,410 + 51,428 = 250,838 Dollars

emerge from the column they pass through a detector cell which generates an electrical signal proportional to the concentration of the component. The Detector should be nonspecific and only be sensitive to the presence of the components in the carrier gas. Ionization detectors are now available which can provide sensitivity to virtually all eluted components in the ppm range or less.

A schematic diagram of a typical gas chromatograph, utilizing ionization detectors, is shown in Figure 4. The primary components of the gas chromatograph shown include a programmer, sample detector valve, an injection valve, a column selector valve, three partitioning columns, three cross-section ionization detectors and an amplifier assembly. The programmer controls the valve operations and sequentially selects the appropriate detector. The sample selector valve allows atmospheric samples to flow through the injection valve. The injector valve injects a known volume of sample into the column system at periodic intervals. The column selector valves are used to prevent the flow of helium and sample through one of the two columns when it is not in use.

The columns consists of: (1) Molecular sieve for permanent gas separation; (2) Carbowax-Amine coated teflon for the separation of NH_3 , CO_2 , H_2O , alcohols, and certain other organic compounds. The cross-section detector housing includes two chambers, one for each of the columns. The amplifier assembly automatically maintains the baseline at the zero level, except when a compound is eluted, and provides automatic attenuation of compound peaks present in concentrations greater than 50 to 100 ppm.

The gas chromatograph is supplied with helium gas from a helium storage reservoir through a regulator and pressure relief valves. The subsystem shown in Figure 2 includes a 90 cubic inch titanium helium storage tank designed to operate at a nominal 6000 psi working pressure. The 90 cubic inch sphere furnishes the carrier gas for continuous operation of the gas chromatograph for 15 days.

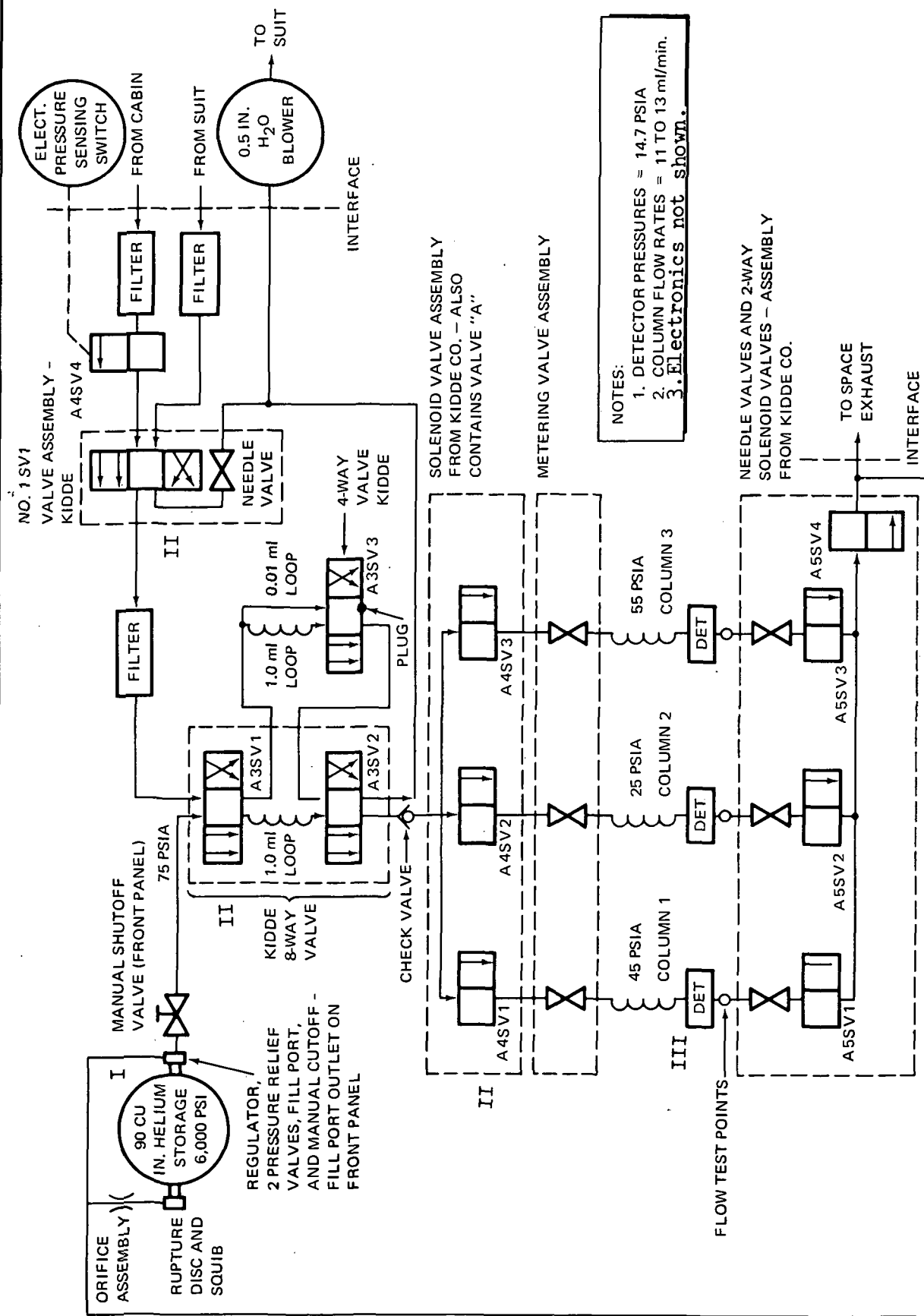


FIGURE 4. GAS CHROMATOGRAPH SYSTEM SCHEMATIC

The analyzer assembly operates with ultrapure helium furnished to the gas circuit at 42 psia ($\pm 2\%$ at 35° to 120°F). Helium enters the gas circuit at the injection valve assembly. It is sequentially controlled by the three valves of this assembly to "inject" the samples contained in any of three sample loops into a column.

From the injection assembly, either pure helium or the sample passes through a check valve to the upper valve assembly at the head of all chromatograph columns. The check valve prevents backflow in the column from diffusing the sample during injection, thereby ensuring sharper elution peaks.

Control of gases to each column and detector cavity is accomplished when the programmer energizes the valves at the top and bottom of a column. Three times during a typical 30-minute automatic cycle, two columns are operating simultaneously. In this case one column is completing an analysis while the other is being purged; however, only one detector is energized. Stable gas flow through the columns is critical for predictable chromatograms. Therefore, gas flow is maintained between 11 and 13 ml/minute for each column by individual meter valve adjustments following the upper valve assembly. For gas flow adjustment, flow through the columns and detector may be monitored through the test point connection below each detector cavity.

Gaseous components elute from each column into its respective detector chamber where they are sensed. The time of this sensing, as measured from the injection time, is determined by the specific adsorption characteristics of the gas with the column material and is therefore used to identify the gas. Actual sensing is accomplished by radioactive tritium foil ionizing the gas in a specific manner so that the ion current normally carried from the detector electrodes is increased. The resulting current is then amplified for electronic readout as a measure of the gas concentration.

Detectors operating pressure is 14.7 psia. A valve subassembly placed at the end of the gas circuit is used to automatically close in the event of operational power failure. Filters are also provided to remove dust particles. For the purpose of developing CER's, the gas chromatograph is construed to comprise the components shown in Figure 4. In addition, electronic components are also provided for the amplification of detector signals, zero compensation, amplifier attenuation and automatic programming. The gas chromatograph will thus consist of the following: 1) helium reservoir, 2) pressure regulator, 3) 8-way valve, 4) sample source valve, 5) solenoid and metering valves assembly, 6) columns and detector assemblies, 7) needle and 2-way solenoid valves, and 8) amplifiers and electronic equipment.

SYSTEM PERFORMANCE AND CHARACTERISTICS:

The gas chromatograph has the following physical and interface characteristics:

| | |
|---------------------------|------------------------------------|
| Columns (2) | Molecular sieve and teflon |
| Helium leakage, estimated | 1.0 cc/hr |
| Operating life | 180 days |
| Shelf life | 44 years estimated (Incl. columns) |
| Volume | 400 in ³ |
| Power | 10 watts maximum |
| Weight | 12 lbs. |
| Accuracy | 3% of full scale |
| Warm up time | one hour |
| Sample purge time | 3 minutes |
| Sample pressure drop | 2 inches of water |

Cost Estimating Relationship:

The gas chromatograph system components have been grouped in four groups, designated as I through IV, as shown in the system schematic, Figure 4. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior year dollar values.

1. Helium Storage Tank:

The CER for the helium gas accumulator, based on a CER developed for high pressure gaseous containers, is given as follows:

$$\text{Helium accumulator fabrication cost} = 18,634 V^{0.377} + 2959 W_{oc} \text{ dollars,}$$

where,

$$V = \text{volume of accumulator} = 0.1 \text{ ft}^3 \text{ and}$$

$$W_{oc} = \text{weight of associated components} = 1.2 \text{ lbs.}$$

The associated components include a pressure regulator, two pressure relief valves, a fill port, an orifice and a manual shut-off valve..

Substituting the values of the variables in the above CER yields:

$$C = 18634 \times (0.1)^{0.377} + 2959 \times 1.2 = 11,380 \text{ dollars}$$

2. Gas Valve Assemblies:

The gas valve assemblies group include three filters, a sample source valve, a check valve, an injection valve assembly and a solenoid valve assembly. The CER for the gas valve assemblies is given by the following relationship:

$$\text{Gas valve assembly fabrication cost } C = 2959 \times W_{GV} \text{ dollars,}$$

where,

$$W_{GV} = \text{gas valve assemblies weight} = 2.8 \text{ lbs.}$$

Substituting the value of W_{GV} in the above CER yields

$$C = 2959 \times 2.8 = 8,285 \text{ dollars}$$

3. Columns and Detectors Assembly

The CER for the columns and detectors assembly is based on CER's developed for adsorption beds and associated components and is given as follows:

Columns and detectors assembly fabrication cost $C = 5288 W_{col}^{0.267} Q^{0.89} + 2959 W_{oc}$ dollars

where,

W_{col} = average column weight = 0.5 lbs,

Q = number of columns used = 2, and

W_{oc} = weight of associated components = 1.5 lbs.

Substituting the values of the above variables in the above CER yields the following:

$$C = 5288 \times (0.5)^{0.267} \times (2)^{0.89} + 2959 \times 1.2 = 11,695 \text{ dollars}$$

4. Amplifiers and Electronic Equipment:

The CER for the fabrication costs of the electronic equipment, mounted on printed circuit boards and including packaging and panel construction, has been based on current similar electronic hardware manufacturing costs and given as follows:

Amplifiers and electronic equipment fabrication cost $C = 150 N_B + 500$ dollars

where,

N_B = number of printed circuit boards per assembly. The gas chromatograph was found to require printed circuit boards for the following functions:

1) amplification of detector signal, 2) zero compensation, 3) amplifier attenuation, and 4) automatic programming. Substituting the value $N_B = 4$ in the above CER yields the following:

$$C = 150 \times 4 + 500 = 1,100 \text{ dollars}$$

Integrated Gas Chromatograph System's Recurring CER:

The integration costs of components and assemblies into the gas chromatograph system are obtained by utilizing the system's recurring CER as defined in previous volumes of this report. Applying the said CER, the first unit cost $C_F = 1.835 \times 1.1 (11,380 + 8285 + 11,695 + 1100 = 65,602 \text{ dollars})$. Assuming the production of two flight-type units, one for flight and one for back-up, then the total hardware cost is given by:

$$C_T = 65,602 \times (2)^{0.89} = 121,690 \text{ dollars}$$

Integrated Gas Chromatograph System's Non-Recurring Cost:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on typical cost breakdown ratios presented in Table I, which are based on actual cost data collected in a space vehicle hardware production program. A system design CER has been developed for the gas chromatograph, similar to that for the mass spectrometer, which combines the effects of both mechanical and electronic system designs. The analysis of a number of cost influencing parameters indicated that mechanical engineering design CER is mainly a function of the number of component types (N) in the system. For electronic system design the cost is a function of the number of printed circuit boards involved. The combined design CER is thus given by the following relation:

$$\text{System design cost } C = 34,935 N + 3000 N_B \text{ dollars}$$

where,

N = number of major components types, considered equivalent to 3, and
 N_B = number of printed circuit boards = 4; substituting the values of variables in the CER yields the following:

$$C = 2 \times 34,935 + 3000 \times 4 = 81,870 \text{ dollars}$$

Values of other non-recurring cost items are listed in Table V, which also shows the breakdown of recurring cost items based on the production of two flight hardware units. All cost figures are in estimated January 1972 dollars.

TABLE V - GAS CHROMATOGRAPH SYSTEM COST BREAKDOWN

| Non-Recurring | | Recurring | |
|---|---------|---|---------|
| System Engineering Design | 81,870 | Flight Hardware Production (2 units) | 66,394 |
| Subcontractor General and Administrative | 42,326 | Subcontractor G&A | 11,220 |
| Subcontractor Fee | 17,766 | Subcontractor Fee | 4,722 |
| Program Management | 6,140 | Program Management | 1,655 |
| System Engineering Development Test | 25,789 | Sustaining Engineering | 2,385 |
| Qualification Test | 16,865 | | |
| Reliability Test | 12,444 | | |
| AGE | 20,058 | | |
| Tooling | 90,548 | | |
| Non-accountable Test Hardware | 18,994 | Sustaining Tooling | 2,056 |
| Specifications, Vendor Coordination and Procurement Expense | 8,187 | | |
| System Integration | 66,888 | Specifications, Vendor Coordination and Procurement Expense | 18,850 |
| Prime's Testing | 41,107 | System Integration | 8,701 |
| Minor Subcontracts | 40,116 | | |
| | 1,883 | Minor Subcontracts | 5,707 |
| Total | 490,890 | | 121,690 |

Total Gas Chromatograph System Cost = 612,580 dollars

Section 5

CONCLUSIONS AND RECOMMENDATIONS

A new method has been developed to predict realistic cost estimates for atmosphere monitoring systems for use in manned earth orbital spacecraft. The cost estimating relationships can be applied parametrically to obtain estimated costs of varying sizes of mass spectrometers or gas chromatographs. The system component costs are identified with respect to such performance-related variables as volume, weight, power and physical characteristics. The results are given in sufficient depth to provide program planners and designers with the necessary cost data for allocation of available resources in a cost effective manner.

Research and technology areas where additional efforts are needed include the development of a flight-type multi-gas trace contaminants mass spectrometer and the renewed development of a flight prototype gas chromatograph similar to the unit previously developed for NASA by the Melpar Company. In flight hardware programs it is also recommended that system design be "frozen" early in the program to minimize the cost escalations associated with engineering changes.

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